FAST 3D MESH GENERATION OF FEMUR BASED ON PLANAR PARAMETERIZATION AND MORPHING

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ABSTRACT

In this paper we present a fast and efficient method for generating a patient-specific femur mesh by morphing a template femur mesh of ten-node tetrahedral elements on a geometry represented in STL format (STL: Surface Tessellation Language). The morphing is constrained through a set of user defined anatomical landmark points. Our method splits the input geometries into open surfaces, and maps each surface individually on a planar parameterization. We morph the parameterizations individually using a regression model based on Radial Basis Functions (RBFs). In experiments our method shows precise results in generating new patient-specific meshes from existing models and in re-meshing.

***Index Terms*—** Medical Imaging, Mesh generation, Radial Basis Functions (RBFs), Parameterization, Morphing, Modeling

1. INTRODUCTION

Medical image processing plays an increasingly important role in medicine for diagnosis, therapy planning, and treatment, among others. In that field, simulation with finite element models is used to explain the human body's functionality and to simulate the result of a chosen therapy. Patient-specific finite element models have been successfully applied to accurately predict strain levels in long bones, see e.g. [1]. It is however well known that the generation of such models is time and effort consuming [2], since the process of segmentation and consequent mesh generation cannot be fully automated.
Using morphing to deform a source shape into a target shape, is a promising approach to the automation of model generation, see e.g. [3]. In this paper we propose a method for fast 3D mesh generation, based on 3D morphing. Classically, morphing is used for photorealistic rendering of surfaces. The novelty of our approach is that we use morphing, instead, to reduce the time of expensive mesh generation for each individual case.
Our method is based on 3D morphing using Radial Basis Functions (RBFs). RBFs have been used for data smoothing, surface reconstruction, and repairing incomplete meshes in [4]. Morphing using RBFs was also introduced by researchers in image warping especially for application to facial expression, see [5]. To our knowledge, morphing based on RBFs has been never used for mesh generation of medical surfaces, as proposed in this paper.
The paper proceeds as follows. In Section 2 we present our morphing technique in detail. In Section 3 experimental results in 2D and 3D are given. In Section 4 we provide a conclusion and future work.

2. MESH GENERATION BASED ON PARAMETERIZATION AND MORPHING

In this section, we present in detail the method we use to morph a pre-generated tetrahedral template mesh on a surfaced patient's geometry represented in STL format. The morphing is constrained through a set of user defined landmark points.
In figure 1, we present the complete framework of our method. Given a 3D mesh and corresponding anatomical landmark points on both outer surfaces, our method proceeds as follows:

1. Extract the surface of the 3D template mesh (parabolic mesh); this step gives us a 2D triangular mesh.
2. Apply our 2D morphing method (described in Section 2.4) to morph the extracted 2D mesh on the STL patient's geometry, resulting in a new 2D mesh (triangular patient FE mesh).
3. Morph inner nodes using result from point 2. and a new RBF interpolation (described in Section 2.5).

2.1. Initialization

The first step of our method is based on morphing the surfaced generic femur mesh on the patient's STL geometry. For this stage we need a set of anatomical correspondences on the two meshes to establish the correct map between the initial and target bone. We use a set of landmark points that the user locates on the femur surfaces, see Figure 2 and Figure 5.

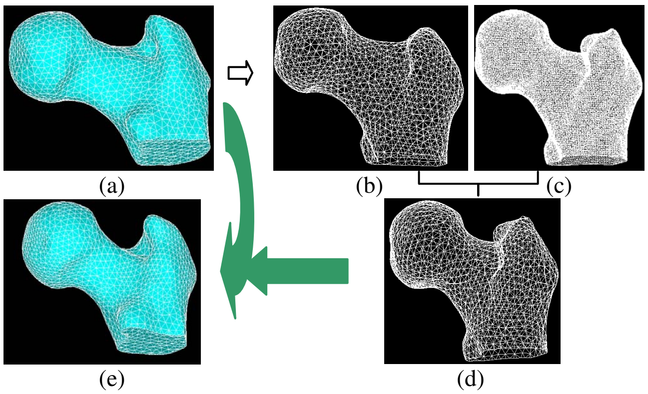

Figure 1: Complete framework of our method; (a) generic 3D tetrahedral mesh; (b) extracted surface (triangular mesh) from (a); (c) Input patient's geometry represented by a STL; (d) Result: patient's triangular mesh; (e) Final Result: 3D tetrahedral mesh of the patient's geometry (using result of (d) and template mesh (a))

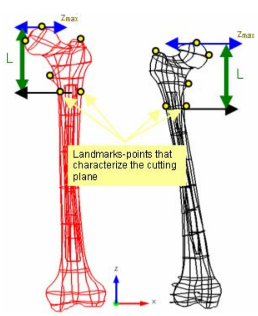

Figure 2: Definition of the cutting plane

2.2. The Cutting Plane

Since the femur has a genus zero topology, it is necessary to split the mesh into several open surfaces. To preserve the anatomical characteristics of the femur, the cutting plane must be selected in a similar way on both femurs. We present two ways to establish the cut: the first is to take the same constant vertical distance from the top point of the femur, as illustrated in Figure 3. The second way, that we found more reliable, is to use a set of user defined landmark points, which define a cutting plane on both inputs.

2.3. Planar Parameterization

After splitting the femur in several genus zero topology meshes, we map each part of the femur onto a planar parameterization. This planar parameterization gives 2D coordinates for each node in the 3D surface. Such a 2D parameterization is important to easily morph the femurs based on the correspondences, and to minimize distortion. We choose a disk for the parameter domain, because of the circular shape of the femur once we cut it and also to obtain a convex domain; which is fundamental to apply our morphing method (explained in Section 2.4). The border of the femur is mapped to the boundary of the circle and the surface of the femur is mapped to the inside of the circle. Our parameterisation method is based on the MIPS algorithm: An Efficient Global Parameterization Method, described in [6]. Figure 3 shows an example of a planar parameterization.

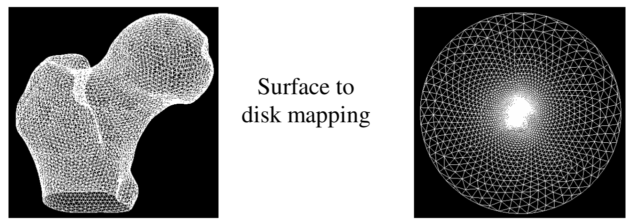

Figure 3: Example of a planar parameterization; (left) generic mesh; (right) 2D parameter domain

2.4. Planar Parameterization Morphing based on RBF Regression

For morphing we use a regression method based on RBF representation. The idea behind this method is that we can interpolate a motion field in the plane using the motion of the reference or landmark points. We denote these points by pi, i=1…n, where n is the number of landmark points. x_i, i=1…N, are all nodes of the mesh, Figure 4 shows an example of such mesh. Intuitively, in this motion filed the motion of a point should depend on its relative distance to the reference points, such that the motion of points will be similar to close landmark points, while the motion of nodes that are far from any landmark point will be interpolated from the flow of all landmark points. Such a behavior can be achieved using a RBF representation, where each landmark point corresponds to the center of a basis function k(, pi), and by solving a linear equation system, that constraints the influence of several motions between reference points and that minimize deformation close to the constrained points.
The motion of a node x_i from the mesh is then represented as a weighted sum over all motions of all landmark points:

$$x^{new} = f\left(x^{old}\right) = x^{old} + \sum_i k\left(x^{old}, p_i\right) \cdot w_i \qquad (1)$$

The coefficients w_i are found using the apparent constraint $f(p_i) = p'_i$, i = 1, …, n, where p_i is the initial position of a reference point on the initial disk and p'_i is the final position of the same reference point on the target disk, as marked by the user.

This leads to a linear equation of the following form:

$$\begin{bmatrix} p_1 - p_1' \\ \vdots \\ p_i - p_i' \\ \vdots \\ p_n - p_n' \end{bmatrix} = \begin{bmatrix} k_{11} & \cdots & k_{1j} & \cdots & k_{1n} \\ \vdots & \ddots & & & \\ k_{i1} & & k_{ii} & & \\ \vdots & & & \ddots & \\ k_{n1} & & & & k_{nn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ \vdots \\ w_n \end{bmatrix} \quad (2)$$

or in matrix form: P = K*W.

Having as many basis functions as constraints, matrix K is square and we have a unique solution for $W=K^{-1} * P$.

In our implementation of the 2D morphing we use the Gaussian RBF as basis function, defined by:

$$k(x, x') = \exp\left(-\frac{\|x - x'\|^2}{2\sigma^2} \right) \quad (3),$$

where σ that determines the degree of smoothness of the interpolation of a given data points, is chosen empirically. If the value of sigma is too small we have a very local deformation, if the value is too big the deformation is global and it may lead to distorted triangles.

Solving the earlier linear system (equation (2)), we find the appropriate w_i. Once we found w_i, we compute the new position of every point in the mesh using equation (1).

Computing all new positions on the target disk, it is easy to get the corresponding nodes on the target femur by projecting it on the surface of the patient's geometry. Figure 5 summarizes the complete framework of our 2D morphing method.

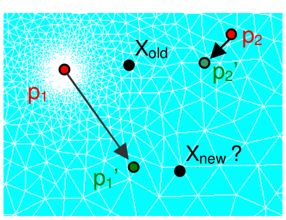

Figure 4: Example of a mesh with two landmark points

2.5. Morphing the Volumetric Mesh

In the previous step we were morphing only the outer surface of the femur. The computation of the inner points is done using the morphed surface (Section 2.3), the initial 3D mesh, and a second RBF interpolation. We recall that applying our 2D morphing technique gives us the new location of all the nodes of the surface, therefore we can use these nodes as the centers of the radial basis functions since we know theirs initial and target positions. We consider the nodes of the surface as landmark points and we apply the same method as described in Section 2, this time in 3D, to define the new positions of the 3D mesh nodes.

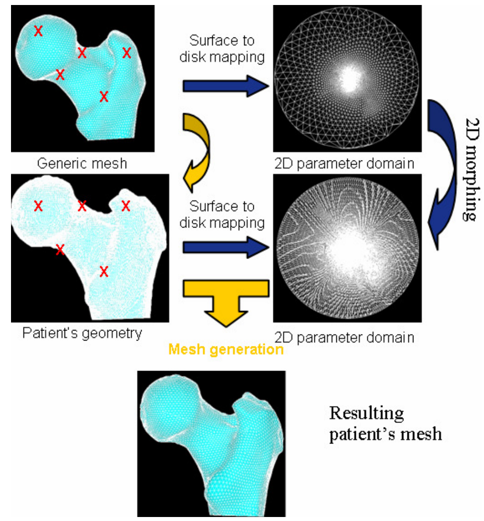

Figure 5: Structure of the first stage of our method (Left column) a generic mesh and a Patient's geometry; (Right column) both are mapped to disks with the same radius. We use the pre-selected reference points (indicated by a red crosses) to morph the parameterization of the mesh onto the parameterization of the geometry. Finally, we use the result from the morphing to adjust our generic mesh to the patient geometry by projecting it on the surface, resulting in the patient mesh (bottom).

3. EXPERIMENTAL RESULTS

To evaluate our work, we investigate two FE models and fifteen patient's geometries represented by STL geometries. Results are shown in Figure 1, Figure 5, and Figure 6. All results have been computed using 5 manually selected landmark points. For parameters σ we use the same value for all selected points based on an empirically choice.

Results for 2D meshes are evaluated by computing the distance between the computed specific patient mesh and the patient's geometry, shown in Figure 7. The resulting error is lower than 0.01 mm on the whole surface. For tetrahedral 3D meshes we compute the aspect ration of both initial and resulting mesh, shown in Figure 8. Element quality, as measured via the aspect ratio metric was found to be comparable to that of the initial (generic) mesh. We apply our 2D and 3D morphing on fifteen patient geometries and we get similar good results with minor distorted triangles in all cases.

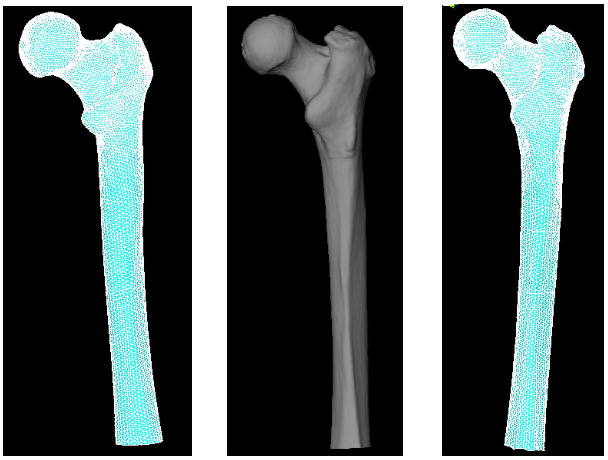

Figure 6: Morphing a generic mesh (left) on a patient's geometry (middle) gives a new FE mesh (right)

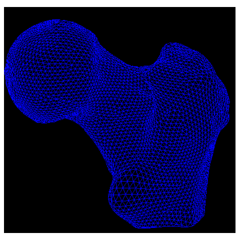

Figure 7: Distance between resulting mesh (resulting from Figure 5) and target geometry. Distance was less than 0.01 mm everywhere

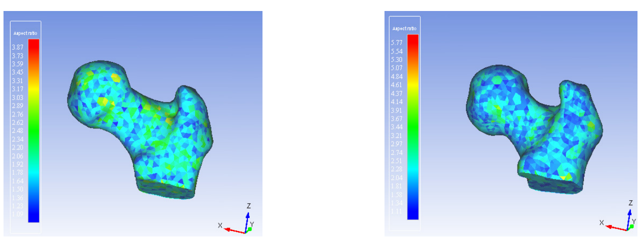

Figure 8: The aspect ratio of the original mesh (left) and the resulting mesh (right)

4. CONCLUSION

In this paper, we proposed a new technique for mesh generation through combining planar parameterization and a morphing method based on RBFs regression. The described method addresses the problem of creating a finite element mesh directly from STL files using a generic FE model and corresponding anatomic user selected landmark points on both femurs (the STL and the generic). Initial experiments of our method tested on fifteen proximal femurs in triangular and tetrahedral mesh show promising results. These results indicate that our morphing method is useful for fast modeling of femur meshes in FE biomedical simulation. Currently, we are integrating our method into a framework for stress and strain simulation.

5. ACKNOWLEDGEMENTS

The authors wish to thank ANSYS Inc. for the use of its Workbench software which was used for planar parameterization, template mesh generation, and visualization in our prototyping work.

6. REFERENCES

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